DETERMINATION OF THE THERMAL CONDUCTIVITY, THE SPECIFIC HEAT AND THE WEIGHT BY VOLUME (GROSS DENSITY) OF INSULATIONS FOR ROCKET TANKS FILLED WITH LIQUID HYDROGEN
PART I. DESCRIPTION OF MEASUREMENT PROCEDURE

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Translation of "Die Bestimmung der Wärmeleitfähigkeit der Spezifischen Wärme und des Raumgewichts (Rohdichte) von Isolationen für mit Flüssigem Wasserstoff Gefüllte Raketentanks"
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ABSTRACT: Experimental research into insulating foams at temperatures down to that of liquid hydrogen (20°K). In addition to a general study of the insulation of tank walls for cryogenic high-energy rocket states, a description is given of various measuring methods of determining the thermal conductivity, the specific heat and the density of insulating materials, together with a comprehensive review of the literature.

1. Introduction

The development of high-energy fuel systems containing /4*
H_2/O_2 is associated with numerous technological and thermodynamic problems. Liquid hydrogen, in addition to its high specific impulse, is moreover characterized by unusual physical properties. Its small density (ρ = 70 kg/m^3) is the cause of a large tank surface-to-unit-mass-of-fuel ratio and this in turn, combined with the low condensation temperature of 20°K, leads to a high heat input. This high heat-flux density induces the condensation of air on the outer wall of noninsulated fuel tanks. The heat of vaporization which is liberated during this condensation is transferred to the hydrogen and induces such an intensive vaporization that a noninsulated high-energy rocket stage is rendered useless. It is for this very reason that it is necessary to insulate such tank walls.

The weight of the thermal insulation, the vaporized fuel, as well as the resulting added tank weight remain in a functional interrelationship to one another and result in a loss of useful payload. This payload loss in turn induces a drop in the high specific impulse of liquid hydrogen.

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*Numbers in the margin indicate pagination in the foreign text.

Consequently, from the previous discussion we find that the thermal insulation of high-energy rocket tanks requires following properties [17]: /8

1. low volume density;
2. low heat-conductance coefficient, also at temperatures below the boiling point of air;
3. sufficient structural strength in order to withstand aerodynamic loads;
4. sufficient elasticity at low temperatures.

Table I gives the properties of some important low-temperature thermal insulation materials. When high-energy fuel systems were first developed, there existed only two types of thermal insulation which satisfied the above-mentioned requirements.

These were the cork insulators and open-cell foams. The open-cell structure has proved to be disadvantageous, in particular in the case of foams. Let the example of polyurethane foam retrace the interesting development of insulators. The polyurethane foams have been appreciably improved by substituting for CO_2 fluorotrichloromethane (R 11) as the foaming agent [4, 19, 20, 34]. This substitution yielded the following advantages:

1. closed cells. Condensation of air on the tank wall is thus to all intents and purposes impossible in the case of cracks existing in the insulator layer;
2. higher resistance to diffusion. The concentration of R 11 in the cells remains constant over a period of several years. The resistance to air diffusion is somewhat lower. However, it takes some weeks before a steady state is established with the surrounding air;
3. higher structural strength;
4. lower heat conductivity. As smaller volume densities are obtained, the insulating effect remains good even after the air has diffused in. By introducing an outer sealing layer which would be characterized by a high resistance to diffusion, the rush of air may be inhibited and the low heat conductance of the heavier R 11 gas can then be utilized. For the sake of comparison let us observe the following heat conductance coefficients at $20^{\circ}C$ [19]:

Polyurethane foamed with CO_2, open cell:

$$\lambda = 0.032 \text{ kcal/m·hr·deg}$$

Polyurethane foamed with R 11, closed cells, immediately after preparation:

$$\lambda = 0.017 \text{ kcal/m·hr·deg}$$

After diffusion of air, some weeks later: /9

$$\lambda = 0.023 \text{ kcal/m·hr·deg}$$

Taking into consideration the requirements that a thermal insulator for rocket tanks must satisfy, under simplifying assumptions, one can derive the following evaluation coefficient, namely $K_{is} = \lambda \cdot \rho$. It is clear that an optimal insulation is considered to be one for which K_{is} has the lowest value.

2. Determination of Heat Conductance Coefficient

2.1. Choice of the determination method. The experimental determination of the heat conductance coefficient of solids has at its disposal a large number of various previously developed processes which, broadly speaking, may be divided into two fundamental classes, namely those whose temperature distribution is steady and those whose temperature distribution is not steady. Nonsteady methods have the disadvantage that the temperature conductance coefficient $a = \lambda \cdot (c \cdot \rho)^{-1}$ is measured so that in order to determine the heat conductance coefficient we require the knowledge of the specific heat c and the density (when dealing with porous media, the "bulk density"). This contrasts with the utmost advantage of the short measurement times. Stationary methods, on the other hand, yield the heat-conductance coefficient directly, so that under comparable conditions greater accuracy may be achieved. Long measurement times, which are the consequence of the temperature equilibrium requiring hours or even days to be attained, are the penalty for the advantages described previously. In the following, therefore, we consider the latter method.

We are only considering systems for which a simple solution of the known Fourier differential equation is available, i.e. plane parallel, infinite lamina (one-dimensional heat flux), infinitely long cylindrical tubes and solid spheres. However, as many insulators could be approximated only with difficulty to the sphere or a tube, it appears that the lamina process is the best one under the circumstances, especially as it had been comprehensively designed as per DIN 52612 ("Determination of Heat Conductance using the Lamina Apparatus") and in the ASTM Designation C 177-45 ("Standard Method of Testing for Thermal Conductivity of Materials by means of the Guarded Hot Plate"). The construction of a "two-plate" apparatus is shown in Fig. 1.

Two plate-like samples are placed symmetrically on each side of a heated plate. Heat is abstracted from the outside surfaces /10
of the samples by means of cooling plates. In order to prevent heat losses to the sides and in order to obtain a one-dimensional heat flux at the centers of the samples, the main hot plate is surrounded by an auxiliary heating ring, whose heat output may be regulated in such a manner that the inner ridge surface is at the same temperature as the principal hot plate. When the cooling plates are at an equal temperature, complete symmetry exists with respect to the center plane and the heat flows at an equal rate through the two plates investigated. The measurement of the

(electrical) power input to the principal hot plate and the measurement of the surface temperatures of the samples suffices for the determination of the heat-conductance coefficient.

When using the one-plate method, the hot plate is screened off at its underside by a counter heat hot plate. The heat output of the counter hot plate is adjusted so that between it and the principal hot plate there exists no temperature gradient. In this manner the total heat abstracted from the main hot plate is forced to flow through the sample. The experimental set-up for the one-plate process is shown in Fig. 2.

The plate methods have been used repeatedly for the determination of heat conductances of thermal insulators at lower temperatures [1, 17, 22, 40, 64, 71, 84]. The ordinary process may be used, without any difficulties, down to the temperature of -100°C but the water must be substituted for by another cooling liquid, e.g. alcohol, propane or pentane. At still lower temperatures, liquefied gases are vaporized on the cooling plate. Since this gives little control over the vapor pressure, the temperature of the cooling plate remains constant. A variation of the mean temperature (which is the average temperature of the two upper surface temperatures of the sample) is therefore only possible by varying the hot-plate temperature. These difficulties may however be circumvented when, instead of a liquid, a gas is used, for example air, as the coolant.

The Philips gas refrigerator which was at our disposal at the Thermodynamics Institute allowed us, in a cold chest, to maintain any temperature in the range between the ambient temperature and -180°C with an accuracy of ± 1°C. A small fan sucks air out of the cold space and blows it against the cooling plate. The temperature fluctuations which were caused by insufficiently accurate temperature control of the cold space were compensated for by ancillary heating in the air stream. The schematic experimental set-up is shown in Fig. 3.

The plate apparatus proper is shown again in Fig. 4. Since the thermal insulator was to be tested also under reduced pressure, due to lack of space particularly, only the one-plate method could be considered. Consequently the regulation requirements became more stringent.

The cooling plate was made of brass and was about 18 mm thick in order to dampen residual temperature fluctuations and to ensure uniform temperature on the side f a c i n g the sample. Since the obstructed heat was of the order of magnitude of 1 watt, special cooling vanes on the air side were found to be superfluous. /11

The diameter of the principal hot plate is 150 mm. According to DIN 52612, the allowable sample thickness is to be between

5 and 14 mm. The hot plates which were 5 mm thick consisted of two soldered copper plates (Fig. 5). The grooves of the thicker plate contained miniature shielded heating elements made by Philips. The counter hot plate was separated from the principal hot plate by a layer of insulator, in order to keep the heat flux small should a temperature gradient exist between them, and well insulated at its upper side to avoid a heat loss in that direction. For the same reason the space between the plates and the walls of the vacuum chamber was filled with a powder-like insulator.

2.2. Measurement and Control Apparatus

2.2.1. Additional temperature control. As has already been mentioned, the temperature of the air in the cold space fluctuates by $\pm 1^{\circ}C$. Without additional temperature control, we would have to use a very thick cooling plate in order that the temperature variations at the sample side of the plate be brought down to a manageable magnitude. As this is impossible, however, we have installed a regulator consisting of a resistance thermometer and a bridge arrangement (thermistor with sensor G of the Haake Co., Berlin) to control this ancillary heating (Fig. 6).

2.2.2. Plate heating. In order to achieve a constant heat flux through the sample, we require not only a constant surface temperature of the sample on the cooling side but also a constant surface temperature on the heating side. In order to ensure this, the power to the principal hot plate is obtained from a direct current stabilizer (Philips direct current power supply PE 4803) which is able to maintain a set required DC voltage with an accuracy of $\pm 0.1\%$. The heat output is measured by a light spot power meter (class 0.1, Hartmann and Braun Co.) (Fig. 7); /12
for very low heat outputs this may probably be replaced by an ordinary current-voltage measurement.

The same power supply feeds the auxiliary and counter heaters. Here, however, we need a special regulator since, as already mentioned, between the principal hot plate on the one hand and the counter- and the auxiliary hot plate on the other, the temperature gradient in the worst case is only allowed to be very small. In order to ensure that this is indeed so, we measured the temperature difference between the outer surfaces of the plate by means of several thermocouple elements in series (Fig. 8) which were connected to a very sensitive light spot galvanometer which in turn activated a photoelectric relay in order to turn on or off a small part of the heating system. (Fig. 7 shows only the regulation apparatus for the auxiliary heating.)

2.2.3. Temperature measurement. The temperature difference between the hot and the cold sides of the sample plate, which is of special importance for the final result, was also

determined by means of thermocouple elements. Our indicator, principally, was a voltmeter with a built-in transistor amplifier having a measurement accuracy of 0.2% (Knick Co., Berlin).

2.2.4. Vacuum. We also plan to investigate the heat conductivity of a thermal insulator at various vacuum pressures. Sporadic, accurate measurements of pressure were made using a vacuometer like the one used by Kammerer.

The indicator was the Thermotron II (Leybold Co.). Simultaneously, using an auxiliary Torrostat and a solenoid valve, we controlled the pressure in the receiver (Fig. 9).

2.2.5. Recording. In order to record all the important measurement and control values, we used a 12-color compensation dot printer (Kompensograph P 288 x 288, Siemens Co.). Due to an advanced automation of regulation loops and because of the above-mentioned recorder, in spite of the long duration of experiments, demands on personnel were reduced to a minimum.

3. The Mechanism of Heat Transport in Thermal Insulators in Light of the Conducted Experiment /13

The heat conductivity of porous thermal insulators is a function of contributions due to radiation λ_s (strahlung), conductance in solids λ_f (fest), gas convection λ_c and conductance in gas λ_g [56].

The contribution of radiation when dealing with thin layers of insulation can assume appreciable magnitude. The radiation properties of the cooling and the hot plate are of utmost importance for the results of the experiment. In general, in compliance with prevailing physical conditions, emissivities of $\varepsilon \approx 0.85$ are recommended. As in our case, when working with aluminum we may take $\varepsilon \approx 0.05$ as an insulation limiting value, this fact is to be taken into consideration while performing our experiment. By varying the thickness of the insulator sample, we are able to achieve the same radiation properties as in [55].

The heat conductance in solids is relatively low. Without taking much trouble it may be checked by filling the insulator with various gases or by evacuating it when using an open cell material. Heat transport by convection becomes appreciable only when the material contains large pores or when there are large temperature gradients and in most cases it may be neglected.

Most important for heat transport is the contribution of heat transfer in gas. By filling the insulators with heavy gases (for example R 11, see above) one may cut down on heat transfer. On the other hand, one may attempt to set the dimensions of the spaces occupied by gas to be smaller than the mean free path of the gas molecules or to increase the mean free path by lowering

the pressure.

4. Determination of Specific Heat

As was the case with the determination of heat conductivity here too, two fundamentally distinct methods are available to us.

It would appear that the specific heat may be determined by using the well-known methods. Since, however, when dealing with thermal insulators the temperature equilibrium is established /14
only after an appreciable lapse of time, special measures have to be adopted [90, 92]. One method available to us is to pulverize and compress the sample under high pressure into a pill and then to determine its heat capacity in a metal calorimeter. One may also use a rotating drum as a calorimeter where the temperature equilibrium is achieved by means of a continual mixing of the powdered insulator material.

The other method is a nonstationary process (see above) which is also especially advantageous, because when required to compute the heating curve of the rocket skin as time goes on, we are first of all mostly interested in the temperature coefficient. There are a number of different methods [73, 74, 79, 85] among which the so-called "nonstationary plate process" seems to be the most useful. The sample, in this process, is imbedded between two hot plates which then suddenly are heated. From the graph showing temperature at the center of the sample vs. time, we are able to find the temperature conductivity.

5. Determination of Volume Density (Bulk Density)

The volume density is determined by weighing and determination of the volume. When dealing with samples with fairly smooth and regular surfaces, we can determine the volume with sufficient accuracy by measuring the dimensions of the sample. For very small samples a volumometer may be used. Of considerable importance for the determination of bulk density (as well as heat conductivity) is the moisture content of the samples. In order to achieve comparable results, only dry samples could be investi- /17
gated. According to DIN 52612, the drying should take place in an oven at 105°C or when using sensitive materials in a desiccator. In order to dry some P_2O_5 we used a vacuum desiccator.

6. Summary

To determine the h e a t conductivity of thermal insulators and insulator materials of construction, we have found the "one-plate" process especially advantageous. The design and the description of the operation of the testing s y s t e m are restricted to experiments in a temperature range from 100°K to 300°K. When the investigation temperature range was extended down to 20°K, a new testing u n i t had to be developed for

that purpose, but the principle of measurements remained unchanged.

7. Bibliography

7.1. Properties of thermal insulator materials for the insulation of cryogenic liquids.

1. Achtziger, J.: "Heat Conductance Measurements on Insulators using the Plate Apparatus at Low Temperatures," Kältetechnik, Vol. 12, pp. 372-375, 1960.
2. Barringer, C.M.: "Urethane Foams for Cold Insulation," Refrig. Engng. N.Y., Vol. 65, No. 4, pp. 53-56 and 108-112, 1957.
3. Bradley, C.B. and Stone, J.F.: "Thermal Insulation for Low-Temperature Application," Chem. Engng. Progress, Vol. 44, No. 9, page 723, 1948.
4. Brochhange, F.K.: "Hard Polyurethane Foams for Cold Insulation: Production Process, Preparation Methods and Application," Kunststoffe, Vol. 53, No. 7, pp. 406-412, 1963.
5. Bum, R.J.: "Analysis of Liquid Hydrogen Storage Problems for Unmanned Nuclear-Powered Mars Vehicle," NASA TN D-587.
6. Buskirk, E.C. and Surland, C.C.: "A New Plastic Low-Temperature Insulation," Chem. Engng. Progress, Vol. 44, No. 10, p. 803, 1948.
7. Cammerer, J.S.: "Recent Foams for Hot and Cold Insulation," Kältetechnik, Vol. 9, pp. 175-177, 1957.

7a. Cammerer, J.S.: Wärme- und Kälteschutz in der Industrie (Heat and Cold Protection in Industry), Springer Press, 1951.

8. Cammerer, J.S. and Dürhammer, W.: "The Effect of Moisture on the Heat Coefficient of Cork Plates Below and Above 0°C," Kältetechnik, Vol. 7, No. 7, p. 195, 1955. /18
9. Chow, C.S.: "The Thermal Conductivity of some Insulating Materials at Low Temperatures," Proc. Phys. Soc. (London), Vol. 61, pp. 206-216, 1948.
10. Edwin, A., Edberg and Schock, W.S.: "Polystyrene Foam from Expandible Beads," Refrigerating Engng. Vol. 65, No. 3, pp. 54-57 and 108-112.
11. Eppinger, C.E. and Love, W.J.: "Bonding Plastic to Metal for High Strengh at Low Temperatures," Advances in Cryogenic Engineering, Vol. 4, 1958.
12. Fried, E. and Costello, F.C.: "Interface Thermal Contact Resistance Problem in Space Vehicles," ARS-Journal, Vol. 32, pp. 237-244, 1962.
13. Smolak, G.R., Knoll, R.H. and Wallner, L.E.: "Analysis of Thermal Protection Systems for Space Vehicle Cryogenic-Propellant Tanks," NASA TR R-130, N 62-16706.
14. Glaser, P.E. and Kayan, C.F.: "Heat Conductance of Powder-Like Thermal Insulators in Different Temperature Ranges and Their Determination," Refrig. Engng. N.Y., Vol. 64, No. 3, pp. 31-35 and 93, 1956.

15. Glaser, P.E. and Reiter, A.: "Thin-Wall Evacuated Heat Insulation Panels," Wash. Ang., 20-25, 62 N 62-15373.

16. Glaser, P.E.: "Advances in Thermal Insulating Materials for Thermal Protection Systems," ARS Techn. Paper (2153-61), 1961.
17. Gray, V.H., Gelder, T.F., Cochran, R.P. and Goodykoontz, J.H.: "Bonded and Sealed External Insulation for Liquid-Hydrogen-Fuelde Rocket Tanks during Atmospheric Flight," NASA Technical Note D-476.
18. Hill, M.L., Alridge, J.M. and Avery, N.H.: "Thermal Insulation for Hypersonic Vehicles," ASME Prep. (62-AV-36), 1962.
19. Hocking, C.S.: "Gas-Filled Foam Insulation 3F," Allg. Wärmetechnik, Vol. 11, No. 10/12, pp. 186-190, 1963.
20. Hocking, C.S.: "On Gas-Filled Plastic Insulation," Kyltekniск Tidskrift (Stockholm), Vol. 21, No. 2, p. 17, 1962.
21. Judge, J.F.: "Linde Offers 'Super' Insulation," Missiles and Rockets, p. 28, October 19, 1959.
22. Kinzer, G.R. Jr.: "Heat Conductance in Expanded Perlite used for the Insulation of Cryogenic Liquids such as Liquid Hydrogen and Liquid Oxygen," ASHRAE J. N.Y., Vol. 5, No. 2, pp. 99-103 and 108, 1963.
23. McClintock, R.M.: "Mechanical Properties of Insulating Plastic Foams at Low Temperatures," Advances in Cryogenic Engng. Vol. 4, p. 132, 1958.
24. McIntire, O.R. and Kennedy, R.N.: "Styrofoam for Low-Temperature Insulation," Chem. Engng. Progress, Vol. 44, No. 8, p. 727, 1948.
25. Miller, R.N., Bailey, C.D., Freeman, S.M., Beall, R.T. and Coxe, E.F.: "Properties of Foams, Adhesives and Plastic Films at Cryogenic Temperatures," Ind. and Engng. Chem. Product. Res. Devt., Vol. 1, No. 4, pp. 257-261, December 1962.
26. Mikesell, R.P. and Scott: "Heat Conduction through Insulating Supports in Very Low Temperature Equipment," J. Research Natl. Bur. Standards (Washington), Vol. 57, p. 6, 1956.
27. Myncke, H.: "Thermal Superinsulation," Communic. Centre. Et. Sci. Techn. Froid (Louvain, Belgium), pp. 23-31, 1962.
28. Olhen, J.R.: "Orbital Storage of Liquid H_2," NASA TN D-559. /19
29. Palmer, B.M. and Taylor, R.B.: "Glass-Fiber Insulation at Liquid Air Temperatures," Chem. Engng. Progress, Vol. 44, No. 8, p. 652, August 1948.
30. Raisch, E. and Weyh, W.: "Heat Conductance in Insulators at Low Temperatures," Zeitschr. für d. Ges. Kälteindustr., Vol. 39, No. 6, p. 123, 1932.
31. Rips: "Determination of the Temperature Field and Heat Losses in Insulations of Liquid Gas Containers," Chimiceskaja Promyslennost, M 62.2, pp. 59-65.
32. Ruccia, F.E. and Mohr, C.M.: "Atmospheric Heat Transfer to Vertical Tanks filled with Liquid Oxygen," Advances in Cryogenic Engng., Vol. 4, p. 307, 1958.

33. Sanders, Victor: "Cellular-Glass Insulation for Low-Temperature Equipment," Chem. Engng. Progress, Vol. 44, No. 10, p. 804, 1948.
34. Schmidt, Wolfgang: "Cold Insulation Properties of Hard Polyurethane Foams," Kunststoffe, Vol. 53, No. 7, pp. 413-420, 1963.
35. Scott, R.B.: Cryogenic Engineering. van Nostrand, Princeton, New Jersey.
36. Seiffert, K.: "The Development of Hot and Cold Insulation Technology," Chemiker-Zeitung, Vol. 79, No. 9, p. 273, 1955.
36a. Seiffert, K.: Der Wärmeschutzingenieur (The Heat Insulation Engineer), Hanser Press, Munich, 1954.
37. Stastny, Fritz: "The New Thermal Insulator Styropor," Kältetechnik, Vol. 7, pp. 75-78, 1955.
38. Stüber, G. and Trauer, H.J.: "The Application of Vacuum-Powder Insulation in the Transportation of Liquefied Gases," Invesitgation at the Technical University, Dresden, Technik (Berlin), Vol. 11, No. 11, pp. 779-783, 1956.
29. Swann, R.T.: "Heat Transfer and Thermal Stresses in Sandwich Panels," NASA Techn. Note 4349, 1958.
40. Verschoor, J.D.: "Thermal Conductivity of Commercial Insulations at Low Temperatures," Refrig. Engng. Vol. 62, No. 9, pp. 35-37, 1954.
41. Weishaupt, J. and Sellmaier, A.: "Insulation of Large Low-Temperature Installations,: Linde Berichte aus Technik und Wissenschaft, No. 11, p. 3-13, April 1961.
42. White, J.F.: "Problems and Developments," Chem. Engng. Progress, Vol. 44, No. 8, p. 647, 1948.
42a. Wilkes, G.B.: "Thermal Conductivity, Expansion and Specific Heat of Insulators at Extremely Low Temperatures, Refrig. Engng., Vol. 52, No. 1, p. 37 ff, 1946.

7.2. The theory of heat conductance in thermal insulators, especially at low temperatures.

43. Buist, J.M., Doherty, D.J. and Hurd, A.R.: "Urethane Rigid Foams: Factors Affecting their Behavior as Thermal Insulants," Supplement to Bull. I.I.F., No. 3, p. 8, 1963.
44. Christiansen, R.M. and Hollingsworth, M.: "The Performance of Glass Fiber Insulation under High Vacuum," Advances in Cryogenic Engng., Vol. 4, p. 141, 1958.
45. Glaser, P.E.: "Heat-Transfer Mechanisms in Evacuated Powder Insulation," Intern. Develop. Heat Transfer. Internat. Conf. Boulder, Colo. 1961, London, 1962, IV; Amer. Soc. Mech. Engrs., pp. 829-837, 1961.
46. Guenther, F.O.: "Relationships among Physical Properties of Foams, such as Composition, Cell Size and Heat Conductance," SPE-Trans, Vol. 2, No. 2, pp. 243-249, 1962. /20
47. van der Held, E.F.M.: "The Contribution of Radiation to the Conduction of Heat," Appl. Sci. Res, (Holland), Vol. A3, No. 3, pp. 237-242, 1952.

48. Huang, Jinn-Huie,and Smith, J.M.: "Heat Transfer in Porous Media with Known Pore Structure (Alundum)," J. of Chem. and Engng. Data, Vol. 8, No. 3, pp. 437-439, 1963.
49. Kemp, N.H.: "Calculation of Heat Transfer from Simularity Boundary-Layer Equations by a Simple Integration Method," Arco-Everett Res. Dept. 137, BSD-TDR-62-171.
50. von Kiss, M.: "Measurement and Theoretical Determination of Heat Conductance of Powders which are Good Conductors," Neue Technik, Vol. 5, pp. 247-256, 1963.
51. Kling, G.: "The Influence of Gas Pressure on Heat Conductance of Thermal Insulators," Allg. Wärmetechnik, No. 8/9, pp. 167-174, 1952.
52. Leidenfrost, W.: "On the Insulation Properties of Fine Granule Powders in Rarified Gases," VDI-Z, Vol. 97, pp. 1235-1242, 1955.
53. Lund, C.E. and Lander, R.M.: "Heat Transfer through Mineral Wool Insulators in Combination with Reflecting Surfaces," ASHRAE J. N.Y., Vol. 3, No. 3, pp. 47-54 and 98-104, 1961.
54. Mikheer, M.A.: "Problems of Heat Transfer," AEC Tr-4511.
55. Poltz, H. "The Influence of Heat Radiation on the Insulating Properties of Porous Insulation Layers," Allg. Wärmetechnik, Vol. 11, pp. 64-71, 1962.
56. Schmidt, T.E.: "On the Heat-Conductance Coefficient of Insulators," Forschung Ing. Wes., Vol. 27, p. 10, 1961.
57. Sparrow, E.M., Echert, E.R.G. and Albers, L.U.: "Thermal Radiation Characteristics of Cylindrical Enclosures," ASME Paper 61-SA-23 NSF Grant 6-10177.
58. Stephenson, M.E. Jr. and Melvin, M.M.: "Thermal Conductivity of Porous Materials," ASHRAE J. N.Y., Vol. 3, No. 2, pp. 75-81, 1961.
60. Swann, R.T.: "Calculated Effective Thermal Conductivity of Honeycomb Sandwich Panels," NASA Techn. Note D-171, December 1959.
61. Verschoor, J.D. and Greebler, P.: "Heat Transfer by Gas Conduction and Radiation in Fibrous Insulation," ASME Trans. Vol. 74, No. 6, pp. 961-968, 1952.
62. Willis, Roger: "Heat Transfer in a Rarefied Gas between Parallel Plates at Large Temperature Ratio," Contract AF 49 (638)-465 N 62-17950.

Find contributions also in [8, 9, 19, 20, 21, 26, 29, 31, 33, 34, 35, 38, 39].

7.3. Apparatus for the determination of heat conductance and the specific heat of thermal insulators, especially at low temperatures:

63. Bradley, C.B.; "The Measurement of Thermal Conductivity of Thermal Insulating Materials by means of the Guarded Hot-plate," Refrig. Engng., p. 337, May 1943.
64. Cammerer, W.F.: "Determination of Heat Conductance of Thermal Insulators at Low Temperatures," Kältetechnik, Vol. 12,

pp. 107-110, 1960.
65. Garner, Stuchell and Adams: "A Method of Determining Thermal Conductivity at Low Temperatures," Refrig. Engng., p. 209, September 1944. /21
66. Gröber, H.: "Heat Conductance in Insulators and Materials of Construction," Zeitschr. VDI, Vol. 54,p. 1319, 1910.
67. Haenlein, Walter: "Modern Semiconductor Cooling Elements," Siemens-Zeitschrift, Vol. 35, No. 4, pp. 264-265, 1961.
68. Held, E.F.M. van der: "Methods for the Determination of the Heat-Conductance Coefficient," Chemisch Weekblad, Vol. 46, p. 16, 1950.
69. Holland, M.G. and Rubin, L.G.: "Apparatus for the Measurement of Thermal Conductivity in the Range 1.7-300°K," Rev. Sci. Instrum. (U.S.), Vol. 33, No. 9, pp. 923-928, September 1962.
70. Jakob, M.: "The Determination Process of the Heat-Conductance Coefficient of Solids in Laminar Form," Z. Techn. Phys., Vol. 7, p. 475, 1926.
71. Jakob, M. and Erk, S.: "Heat Conductance of Ice Between 0°C and -125°C," Z. für die Gesamte Kälteindustrie, No. 12, 1929.
72. Knappe, W.: "The Determination of Thermal Constants of Bad Thermal Conductors using a Two-Plate Apparatus without Protective Ring," Z. Angew. Physik, Vol. 12, No. 11, pp. 508-514, 1960.
73. Kunze, P.: "Testing a Heat-Conductance Determination Method," Wissens. Z. d. Univ. Rostock, Vol. 2, No. 1, p. 11, 1952.
74. Mann, G. and Forsyth, F.G.E.: "Heat-Conductance-Coefficient Determinations of Insulators using the "Heated Probe Method," Modern Regrigeration, Vol. 59, No. 699, p. 188, 1956.
75. Möhrke, Peter: "Heat-Conductance Determinations using Domestic Insulators in Laminar Form," Wissensch. Z. d. Univ. Rostock, No. 1, p. 29, 1951/52.
78. Müller, Heinz: "The Construction and Application Parameters of Peltier Systems in Refrigeration Installations," Siemens-Z., Vol. 37, No. 5, pp. 383-388, 1963.
79. Pellane, C.M. and Bradley, C.B.: "Rapid Heat-Flow Meter Thermal Conductivity Apparatus," Materials Research and Standards, Vol. 2, p. 7, 1962.
80. Petuchow, B.S.: Experimentelle Untersuchung der Wärmeubertragung (Experimental Investigation of Heat Transfer), VEB Verlag Technik, Berlin, 1958.
81. Phillips, L.W. and Robinson, H.A.: "'Mean' Temperatures in Thermal Conductivity Measurements," Refrig. Engng., Vol. 51, No. 1, p. 43, 1946.
82. Poensgen, R.: "Technical Process for Determining the Heat Conductance of Materials in Laminar Form," Zeitschr. VDI, Vol. 56, p. 1653, 1912.
83. Powell, R.L., Rogers, W.M. and Coffin, O.: "An Apparatus for the Determination of Heat Conductance of Solids at Low Temperatures," J. Res. Natl. Bur. Standards, Vol. 59, No. 5,

pp. 349-355, 1958.
84. Rowley, F.B., Jordan, R.C. and Lander, R.M.: "Thermal Conductivity of Insulating Materials at Low Mean Temperatures," Refrig. Engng., Vol. 50, No. 6, p. 541, December 1945.
85. Somers, E.V.: "High-Speed Guarded Hotplate Apparatus for Thermal Conductivity of Insulating Materials," Review of Scientific Instruments, Vol. 22, No. 8, August 1951.
87. Verschorr, J.D. and Wilbur, Adam: "A Rapid Heat-Meter Thermal Conductivity Apparatus," ASHVE Trans., Vol. 60, p. 329, 1954.
88. White, G.K.: Experimental Techniques in Low-Temperature Physics. Clarendon Press, Oxford, 1959. /22
90. Wilkes and Wood: "The Specific Heat of Thermal Insulators: Heating, Piping and Air Conditioning, ASHVE Journal, Vol. 14, p. 370, June 1942.
91. Wilkes, G.B.: Heat Insulation. John Wiley and Sons, New York, 1950.
92. Yokobori, S. and Nakagawa, M.: "The Determination of Heat-Conductance Coefficient of Various Insulators," Kältetechnik Vol. 9, p. 186, 1957.

Also relevant are articles in [1, 9, 14, 17, 22, 26, 30, 35, 40, 44, 47, 50, 61].

The Entwicklungsring Nord group is much indebted to Professor Dr. Ing. J. Löffler of the Institute for Thermodynamics and Refrigeration at the Technical University, Berlin, for conducting this investigation.

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TABLE I: PROPERTIES OF THERMAL INSULATING MATERIALS

Insulating Material	Remarks	Density	Heat Conductivity Coefficient at a mean temperature of					Specific Heat (0°C)	Tensile str. (0°C)	Hydroscopicity (0°C)	Reference No.
			-200°C	-150°C	-100°C	-50°C	0°C				
		kg/m³	kcal/m·hr·°C					kcal/kg·°C	kp/cm²	vol %	
Powder-like Fillers:											
Puffed Perlite	74% silicic acid, 13% Al_2O_3	30-40		0.018	0.022	0.028	0.036				17
		40-45		0.015	0.021	0.028	0.034				17
		60		0.02	0.027	0.033	0.039				17
Carbonic acid	Magnesia	131	0.018		0.025	0.029	0.033				7a
Cork	Expanded slags	37	0.008		0.018	0.022	0.028				7a
	" "	45					0.027				36a
	Burned	101	0.013	0.017	0.022	0.027	0.033				9
	Powder	104					0.038				91
Diatomac. earth	Inf. earth	54	0.012	0.015	0.019	0.025	0.03				30, 7a
		85			0.012		0.018				91
		122				0.017	0.019				84
		125		0.012	0.015						40
Natural Fibers:											
Glass wool		27				0.023	0.031	0.22			84
	Impregnated	63					0.029				92
	Bonded	176		0.014	0.018	0.023	0.028				91, 42a
Slag wool		95	0.009	0.013	0.017	0.022	0.027				30
		119	0.01	0.014	0.018	0.023	0.028				30
		197	0.010	0.014	0.020	0.027	0.033				9
Stone wool	Sillan	50					0.028	0.2	0.001	large	36
	Sillan	100					0.030		0.03		36
	Novolan	209					0.034				92

TABLE I (cont'd)

Insulating Material	Remarks	Density	Heat Conductivity Coefficient at a mean temperature of					Specific Heat (0°C)	Tensile str. (0°C)	Hydroscopicity (0°C)	Reference No.
			-200°C	-150°C	-100°C	-50°C	0°C				
		kg/m³	kcal/m·hr·°C					kcal/kg·°C	kp/cm²	vol %	
	Impregnated	251				0.031	0.037				84
	Pitch binder	229			0.0.19	0.025	0.032	0.185			91
	Pitch binder	266		0.022	0.023						40
	Synthetic resin binder	263		0.019	0.024						40
	"	229		0.016	0.021	0.027	0.031				42a
	Felt	100		0.014	0.019						40
Cotton Wool		42	0.009	0.014	0.019	0.026	0.034				9
Solids:											
Cork sheets	Expanded	95					0.029				56
	Expanded	104				0.028	0.036				84
	Expanded	107				0.024	0.032				7a
	Expanded	110	0.012	0.019	0.024	0.029	0.032				91, 42a
	Expanded	128				0.029	0.032				84
	Expanded	150		0.022	0.027		0.032	0.34	0.5	6-12	36, 40, 36a
	Expanded	160				0.026	0.035				7a
	Expanded	166					0.038				92
	Expanded	195				0.033	0.036				84
Cork sheets	Expanded	250					0.039				56
	Expanded	300					0.043				56, 36a
	Expanded	450					0.051				56
	Sandwich	210		0.029	0.035	0.041	0.047				17
	Sandwich	250		0.027	0.032	0.038	0.043				17

TABLE I (cont'd)

Insulating Material	Remarks	Density	Heat Conductivity Coefficient at a mean temperature of					Specific Heat (0°C)	Tensile Str. (0°C)	Hydroscopicity (0°C)	Reference No.
			-200°C	-150°C	-100°C	-50°C	0°C				
		kg/m³	kcal/m·gr·°C					kcal/kg·°C	kp/cm²	vol %	
Synthetics:											
Foams:											
Foam rubber	Rubatex	78		0.012	0.020	0.024	0.027	0.22		small	91, 42a
	Onazote	40					0.019			small	92
	"	64					0.025			small	56
		55					0.032			small	92
		86				0.02	0.028			small	56, 7a
		72		0.015	0.02					small	40
Iporka	Basis: urea formaldehyde	13					0.027				56
		13					0.031				56
		15					0.03	0.33	0.1	65	36a
		16-25					0.029				56
		22-24					0.028				56
Phenolic resin	Troporite	66					0.03		0.5	30	92
Polyurethane foam	Moltopren	42					0.023				56
	Foaming agent										
	CO_2	57				0.024	0.029				34
	R 11	44					0.023				34
PVC	Foamed	163					0.035				92
Polystyrol		40					0.03				92
	Styropor	25					0.027	0.33	0.5	2	36
	Styropor	38					0.031				33
	Expansit KS	24		0.014	0.02						40, 37

TABLE I (cont'd)

Insulating Material	Remarks	Density	Heat Conductivity Coefficient at a mean temperature of					Specific Heat (0°C)	Tensile Str. (0°C)	Hydroscopicity (0°C)	Reference No.
			-200°C	-150°C	-100°C	-50°C	0°C				
		kg/m³	kcal/m·hr·°C					kcal/kg·°C	kp/cm²	vol %	
Foam glass		125					0.04				92
		147		0.041	0.045						40
		160				0.034	0.047	0.2	5.9	small	33
		165				0.042	0.048				84
		170	0.035	0.041	0.046	0.050	0.053	0.22			91
		170					0.041				92, 42a
		180					0.049				9
Mica	Expanded (zonolite)	216	0.0243	0.03	0.037	0.047	0.057	0.17			
Multi-Layer Insulation (Bad Conductor, Good Insulator):											
Isoflex		12				0.042					92
Linde SJ 4	Temp. range	75			0.000055						17
Linde SJ12	90-300°K	40			0.00024						17
Linde SJ44	Temp. range	75			0.00003						17
Line SJ99	30-530°K	120			0.000015						17

Table II: Key to Headings

a	bending, according to DIN 53423 ($kp \cdot cm^{-2}$)
b	notch, according to DIN 53453 ($kp \cdot cm^{-2}$)
c	shear, according to DIN 53422 ($kp \cdot cm^{-2}$)
d	E-modulus from bending test ($kg \cdot cm^{-2}$)
e	compression, according to DIN 53421 ($kp \cdot cm^{-2}$)
f	tension, according to DIN 53571 ($kp \cdot cm^{-2}$)
g	foam material designation
h	range of bulk density ($kp \cdot m^{-3}$)
i	applicable temperature range (^{o}C)
k	heat conductance = f (mean temperature) ($kcal^{-1} hr^{-1} {}^{o}C^{-1}$)
l	range of heat conductance ($kcal^{-1} hr^{-1} {}^{o}C^{-1}$)
m	specific heat at $0^{o}C$ ($kcal \cdot kg^{-1} {}^{o}C^{-1}$)
n	mean thermal expansion coefficient
o	bulk density · heat conductance
p	per cent water-vapor intake (Vol. %)
r	water-vapor/diffusion-resistance coefficient
s	pore size (mm)
t	pore structure

TABLE II

Exp. No.	a	b	c
1	Polyurethane formed with Frigen	32...64	-253...+127
2	Polyurethane Moltopren (Bayer)	16...500	-200...+100(+180)
3	Polyurethane, foamed with CO_2	30...150	...+100(+150)
4	Polyurethane, foamed with R14	44	
5	Polyurethane, foamed with R11	30...50	...+ 60(+ 80)
6	Polystyrol Styrofoam 33		
7	Polystyrol Styrofoam 22		
8	Polystyrol	40	
9	Polystyrol Styropor	25...38	
10	Polystyrol Expansit KS	24	
11	Polystyrol Styrofoam	27...38	...+ 70
12	Polystyrol Styropor P	20...60	...+ 70(+ 80)
13	Polystyrol Styropor P	60	...+ 90(+100)
14	Phenolic resin Phenodus (Albert)	40...100	-180...+130(+180)
15	Phenolic resin Troperit	66	-200...+130(+180)
16	Phenol-formaldehyde	40...60	-200...+140(+180)
17	Urea formaldehyde resin Isis foam	4...25	...+200
18	Urea formaldehyde resin Iporka	13...25	
19	Epoxy resin Araldit	300	
20	Epoxy foam		-223...+127
21	Polyether foam, soft		-253...+127
22	Polyethylene with gas	32...35	...+ 70(+ 90)
23	Teflon		
24	Polyester-polyurethane		-248...+ 80
25	Urethane	16...400	(+ 90)
26	PVC with gas	30...60	...+ 70(+ 80)
27	Foam rubber Rubatex	78	
28	Foam rubber Onazote	40...86	2
29	Foam glass	125...180	
30	Mica Zonolite, expanded	216	
31	PVC, foamed	163	

TABLE II (cont'd)

Exp. No.	d at a mean temperature in °C							e	f
	-250	-200	-150	-100	-50	0	25		
1		0.0075	0.0121	0.016	0.0194	0.022		0.0075...0.025	
		0.01	0.015	0.0191	0.0227	0.0248			
2		0.016			0.024	0.0335	0.021/34	0.0160...0.034	
3					0.024	0.029	0.031	...0.029	
4						0.023		...0.023	
5							0.020	...0.020	
6			0.0137	0.02	0.0279	0.0375		0.0137...0.038	
7		0.007	0.0124	0.0175	0.0233	0.0296		0.007 ...0.0296	
8						0.03		...0.030	0.33
9							0.027/31	...0.031	0.33
10			0.014	0.02				0.014 ...	0.33
11							0.028	...0.028	
12							0.027	...0.027	
13							0.027	...0.027	
14		0.011	0.014	0.018	0.022	0.022/35	0.024/27	0.011 ...0.027	
15			0.0135			0.03		...0.030	
16			0.0135				0.028	...0.028	
17							0.024/27	...0.027	
18						0.027/31		...0.031	0.33
19							0.016	...0.016	
20									
21									
22							0.028	...0.028	
23	0.015?	0.0185	0.0208	0.0219	0.023	0.0236	0.024	0.0185...0.024	
24									
25								...0.037	
26							0.028	...0.028	
27			0.012	0.020	0.024	0.027		0.012 ...0.027	0.22
28			0.015	0.02	0.02	0.019/32		0.015 ...0.032	0.22
29		0.035	0.041	0.045/46	0.034/50	0.041/51		0.035 ...0.053	0.22
30		0.0243	0.03	0.037	0.047	0.057		0.0243...0.057	0.17
31						0.035		...0.035	

TABLE II (cont'd)

Exp. No.	g	h	i	k	l	m
1		0.24...1.59				
2		0.26..17.0		5.3...20		closed cell?
3		0.87...4.35	low	5 ...25 (ave)	0.01...1.0	65-80% closed cell
4		...1.01				closed cell?
5		0.60...1.00	very low	60 (very high)	0.01...1.0	95% closed cell
6						closed cell?
7						closed cell?
8		...1.20	2			closed cell?
9		0.78...1.18	2	50...100(720)		closed cell?
10		0.34	2			closed cell?
11	$4.0 \cdot 10^{-5}$	0.76...1.06		100	0.2 ...2.0	closed cell?
12	$5.0 \cdot 10^{-5}$	0.54...1.62	30	40...300	0.005..1.0	closed cell?
13	$5.0 \cdot 10^{-5}$	...1.62		200..300	0.005..0.05	closed cell?
14		0.44...2.70	10-93% rL	30...300		
15		...1.98	30	90		
16		1.12...1.68	low	21.6...62.4	0.01...1.0	50% closed cell
17		0.11...0.68	32-95% rL	low		open cell
18		0.40...0.78	65	1.7		
19		...4.80				
20						
21						
22		0.89...0.98			0.5 ...1.0	
23						
24						
25		0.60...14.9				
26		0.84...1.68	very low	very high	0.01...1.0	closed cell?
27		0.94...2.11	small			
28		0.60...2.75	small			
29		4.38...9.54	small			
30		5.25..12.3				
31		...5.71				

TABLE II (cont'd)

Exp. No.	n	o	p	r	s	t
1		up to 4.8				
2	1...190	1...20	4...195	0.4		
3	1.5... 20					
4						
5	1.5... 3.0					
6						
7						
8	(0.5)					
9	(0.5)					
10						
11	2.0... 2.5					
12	1.5... 4.5					
13	4.5					
14	1.8... 7.8	1.2...5.4	3.0...6.5	0.06...0.08	0.8...4.6	120...210
15	4.9... 6.2	3.3...4.4	4.2...5.5	0.08...0.09	2.5...4.1	155...210
16	2.0... 3.0	1.2...3.3	3.0...4.2	0.06...0.10	0.8...2.5	120...155
17						
18	(0.1... 0.5)					
19	126					
20	up to 4.2	up to 4.2				
21		0.5...2.3				
22	2.5					
23						
24		up to 5.2				
25						
26	2.0... 6.5					
27						
28						
29	(5.9)					
30						
31	(0.5)					

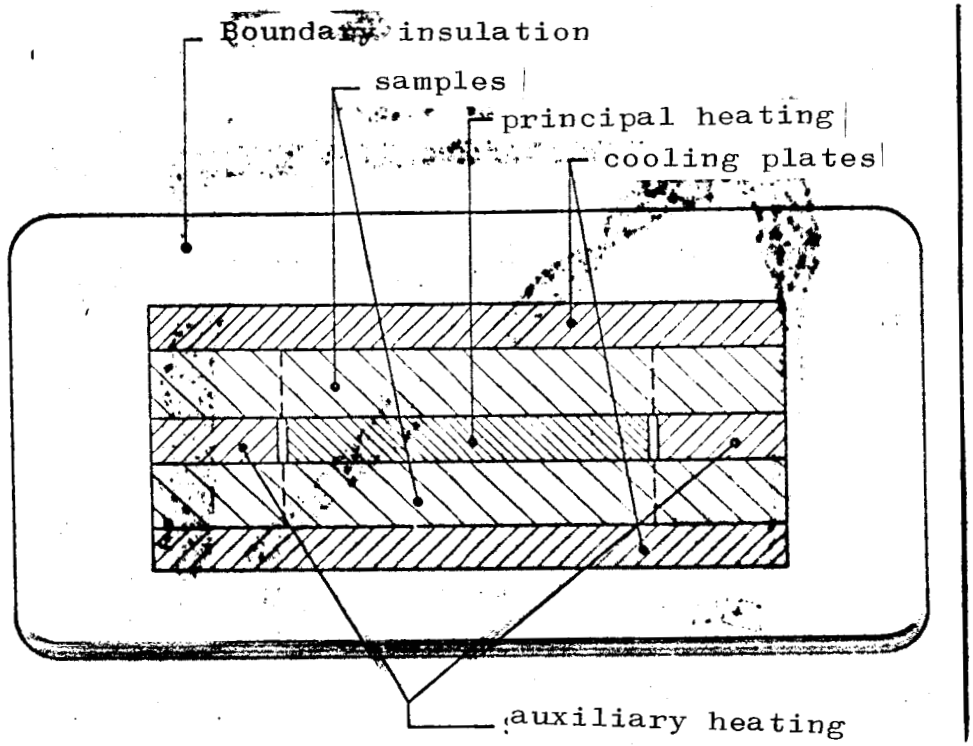

Figure 1.

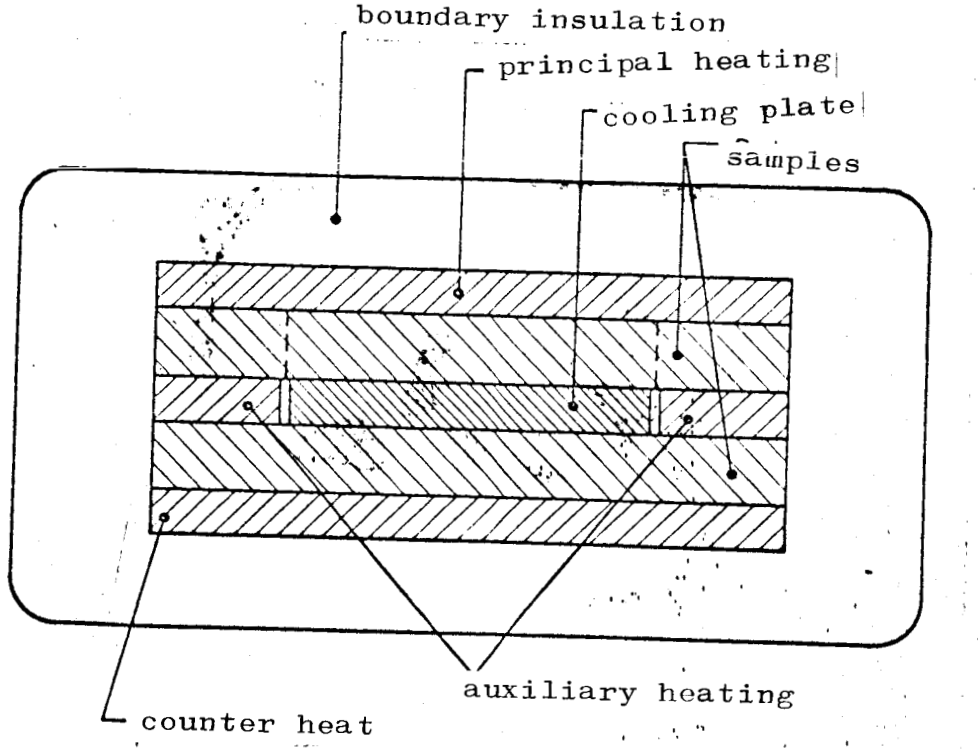

Figure 2.

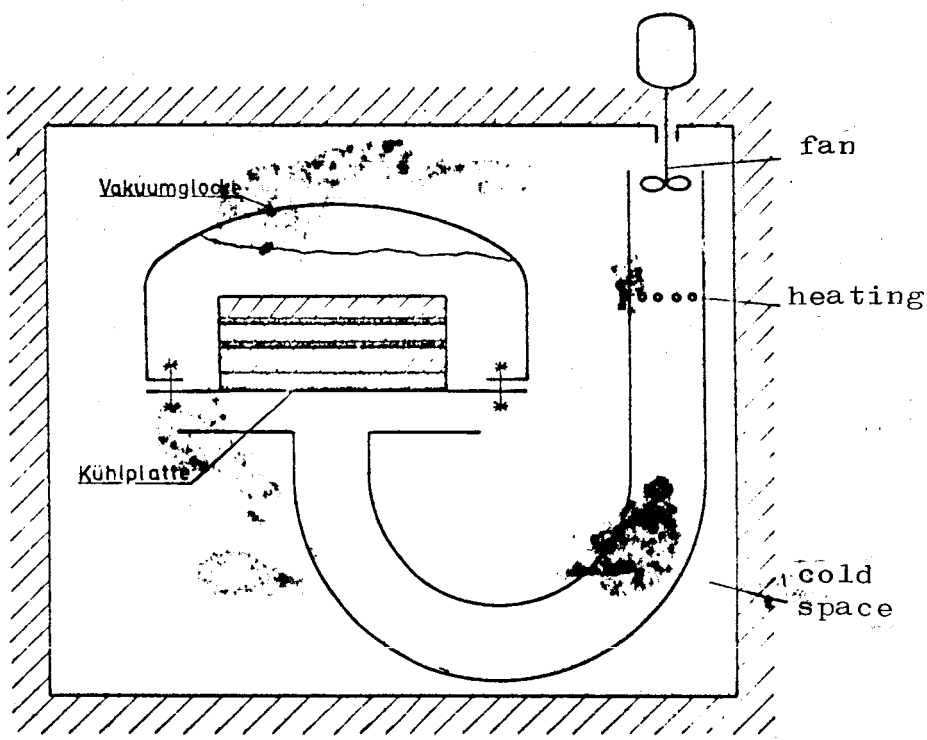

Figure 3.

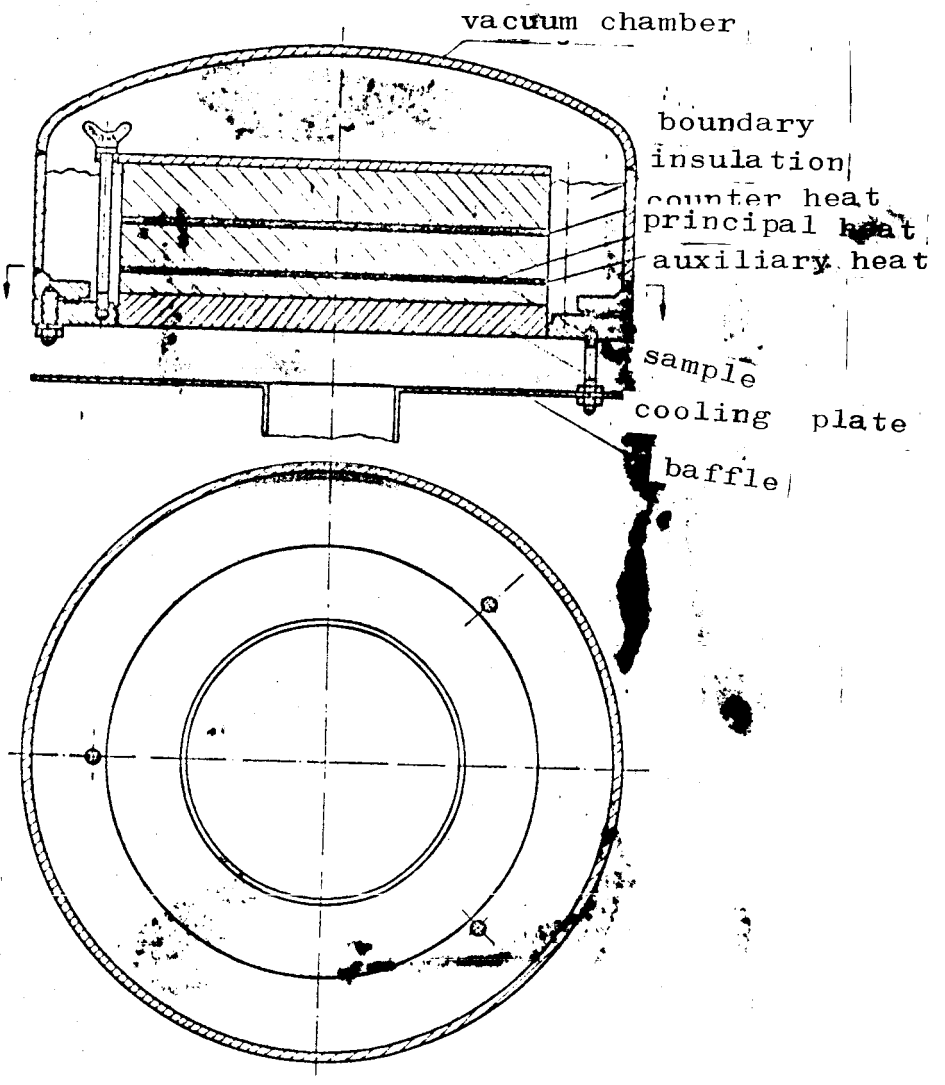

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Figure 4.

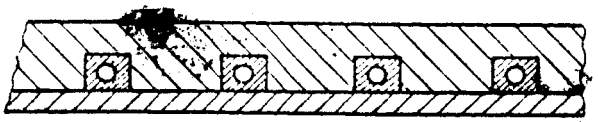

Figure 5.

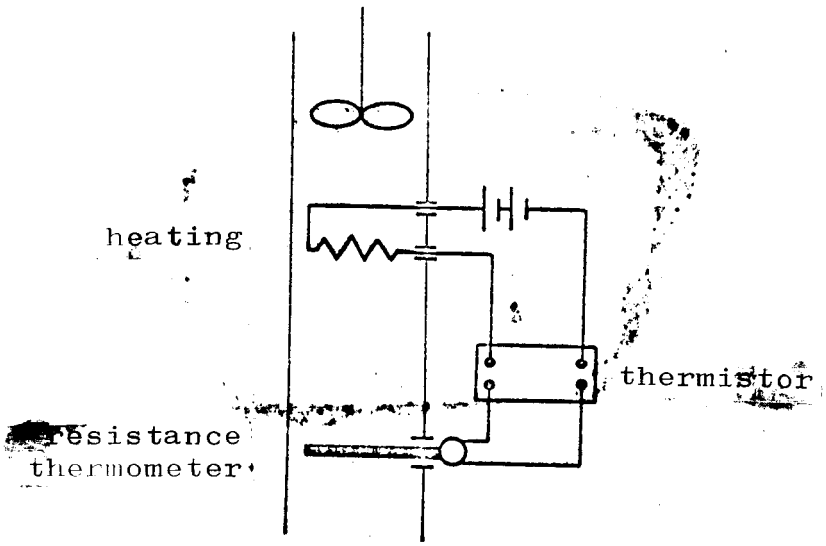

Figure 6.

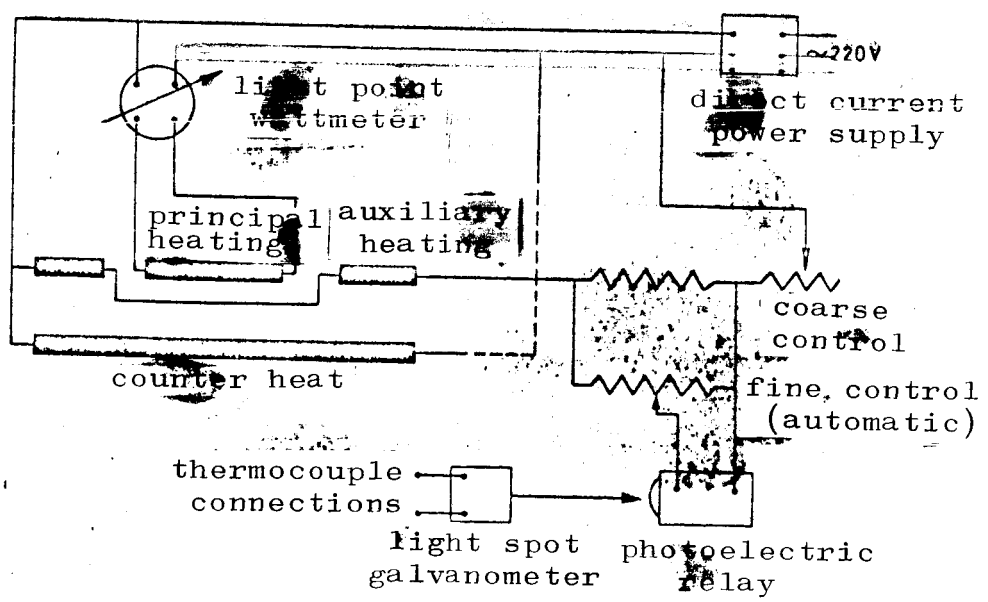

Figure 7.

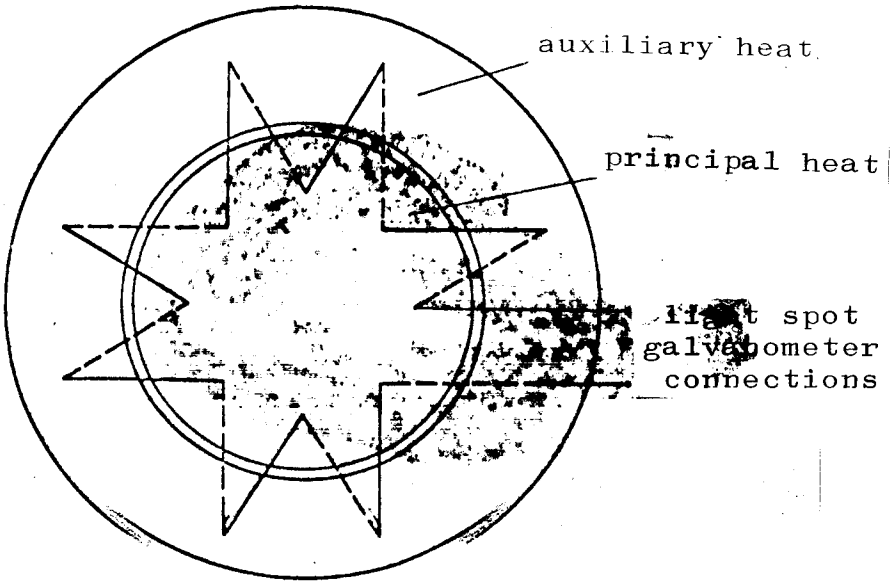

Figure 8.

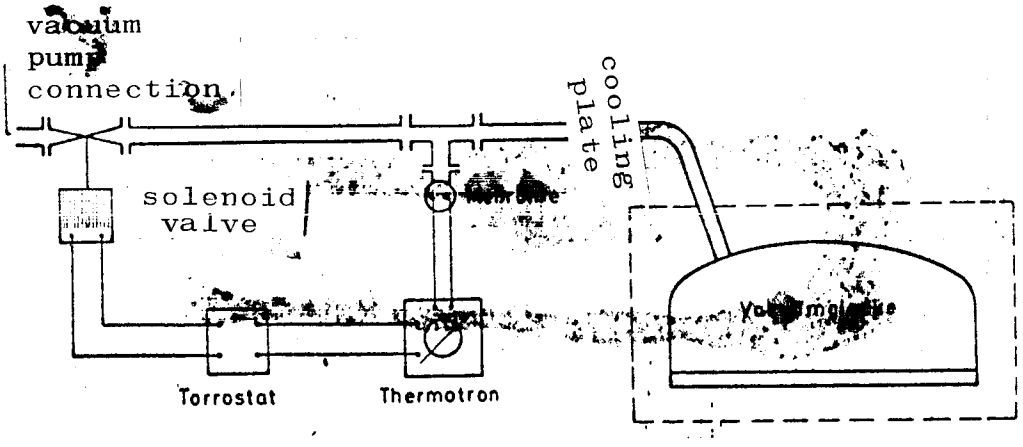

Figure 9.